Tracking fast small color dipoles through strong gluon fields at the LHC

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We argue that the process $\gamma + A \to J/\psi +$ " gap" $+ X$ at large momentum transfer q^2 provides a quick and effective way to test onset of a novel perturbative QCD regime of strong absorption for the interaction of small dipoles at the collider energies. We find that already the first heavy ion run at the LHC will allow to study this reaction with sufficient statistics via ultraperipheral collisions hence probing the interaction of $q\bar{q}$ dipoles of sizes ~ 0.2fm with nuclear media down to $x \sim 10^{-5}$.

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Soon after J/ψ was discovered, the J/ψ photoproduction experiments on nuclear targets have established that nuclei are practically transparent to the J/ψ's produced at photon energies in the range $\sim 20\,\text{GeV} \div 120\text{GeV}$ [1, 2]. The absorptive cross section, $\sigma_{abs}^{J/\psi N}$, was found to be close to $\sim 4\,\text{mb}$ that is much smaller than the cross section of interaction of ordinary mesons $\sim 25\,\text{mb}$. The observed transparency is natural within the Low-Nussinov model of two gluon exchange where the cross section of hadron interaction with a small color singlet dipole quark-antiquark configuration in the photon wave function is proportional to the square of the transverse size of the color dipole [3, 4]. Note, that the average size of $c\bar{c}$ configurations involved in photoproduction of J/ψ is significantly smaller than the J/ψ size. Such suppression of interactions of small dipoles is well known effect in electrodynamics - for example, a muonium can propagate through the media much easier than a positronium.

Within the leading $\ln Q^2$, $\ln(1/x)$ approximations of perturbative QCD one expects (in difference from the Low - Nussinov model) that the cross section of the interaction of small dipoles with hadrons should increase rapidly with increase of invariant dipole-hadron energy $W_{\gamma N} = \sqrt{s}$ due to the growth of the gluon fields in hadron targets at small $x \propto s^{-1}$:

$$\sigma_{dip-T}(x,d) = \frac{\pi^2}{3} F^2 d^2 \alpha_s(\lambda/d^2) x G_T(x, \lambda/d^2), \qquad (1)$$

where $F^2 = 3(4/3)$ is the Casimir operator for the two-gluon ($q\bar{q}$) dipole, and $\lambda \sim 4-9$. For a dipole of a size ~ 0.25 fm relevant for production of J/ψ Eq.(1) corresponds to energy dependence $\propto s^{0.2}$ and describes well behaviour of the both exclusive electro production of vector mesons and the inclusive cross section of deep inelastic electron-proton scattering scattering observed at HERA, for a review and references see [5].

A naive extrapolation of the observed pattern to LHC energies indicates that the strength of this interaction may reach values comparable to that experienced by light hadrons, leading to a new regime of strong interaction physics at the LHC characterized by a strong absorption of small color dipoles by the media. On the other hand it is evident that to avoid conflict with probability conservation starting from some energies such rapid increase of cross section should be tamed.

So, the question is whether it will be possible at LHC to observe this new perturbative QCD regime when the coupling constant is small but the interaction is strong. In practice, it is very difficult to devise a high energy probe for virtualities of few GeV^2 for the hadron colliders especially for the high energy strong interactions involving nuclei where gluon densities per unit area are higher and where new high gluon density physics should be enhanced. Such a problem is absent for electron - ion colliders but these colliders are far in the future.

An alternative which we discuss here is to use ultraperipheral collisions (UPC) of ions at the LHC in which one of the nuclei serves as a source of quasireal photons and another one as a target. The recently published study [6] demonstrates that it is feasible to select UPC at the LHC and that the rates for many processes of the dipole - nucleus interactions are high enough. This includes the process of coherent photoproduction of J/ψ [7]. However, this process could only be effectively studied up to relatively small energies $W_{\gamma N} \sim 130\,\text{GeV}$ due to the inability to separate contributions due to the lower and higher energy photons emitted by two colliding ions. Here we suggest a strategy which avoids the above mentioned shortcoming of the coherent J/ψ production. It is based on the study of the large momentum transfer $-t \equiv q^2 \equiv (p_\gamma - p_{J/\psi})^2$ process: $\gamma + A \to J/\psi + \text{gap} + X$. In addition to the theoretical advantages which we will explain below it also has some appealing observational features. Observation of J/ψ and hadrons allows to determine unambiguously which of the nuclei emitted the photon. As a result it is possible to observe the process up to $W_{\gamma - N} \sim 1\text{TeV}$. Besides, acceptance of the all three LHC detectors which plan to study heavy ion collisions is sufficiently large for the discussed kinematics.

At first, let us briefly consider the main features of the elementary reaction $\gamma + p \to J/\psi + \text{gap} + X$ in a case of a proton target which was extensively studied at HERA. This process belongs to a class of reactions introduced in [8, 9] where selection of large $q^2 \gg 1/r_N^2$ ensures that

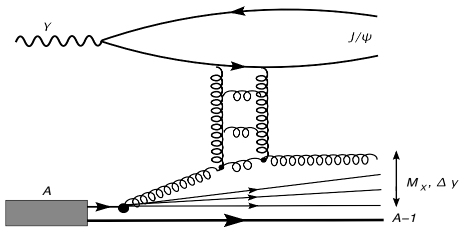

FIG. 1: The typical perturbative QCD diagram for J/ψ production with gap.

transverse momenta remain large in all rungs of the gluon ladder and therefore two gluons are attached to one parton in the target, see Fig. 1. As a result the cross section can be written in a factorized form as a product of the gluon density in the target (the kinematics can be chosen so as the correction due to scattering off the quarks which we will not write below explicitly will be small) and the elastic cross section of scattering of a small dipole off a gluon:

$$\frac{d\sigma_{\gamma T\to J/\psi X}}{dq^2 d\tilde{x}} = \frac{d\sigma_{\gamma g\to J/\psi g}}{dq^2} g_T(\tilde{x}, q^2), \tag{2}$$

where $g_T(\tilde{x}, q^2)$ is the gluon distribution in the target, $\tilde{x} = q^2/(M_X^2 - m_N^2 + q^2)$ and M_X is the invariant mass of the produced hadron system. Though it is not practical to measure M_X^2 directly, it can be expressed with a good accuracy through Δy, the rapidity interval occupied by the system X as

$$\Delta y = \ln(\sqrt{q^2}/\tilde{x} m_N). \tag{3}$$

The HERA data for the large q^2 and rapidity gap photoproduction of J/ψ off the proton target are consistent with the expectations of the models based on the factorization approximation in Eq.(2) and QCD inspired models for the $\gamma g \to J/\psi g$ amplitude, see Refs. [10], [11] for recent data analyses and references.

Now let us analyse the effects arising in a case of the nuclear target in which the color singlet dipole produced in the photon interaction with one of the nuclear nucleons passes through nuclear medium before to form the J/ψ. Firstly, we need to estimate the average dipole size, d, which enters in the elementary $\gamma g \to g J/\psi$ amplitude. The overlapping integral between photon and charmonium wave functions is determined by c-quark momenta $k_t \sim m_c$. For a two body $c\bar{c}$ system with Coulomb interaction one finds $d \approx \sqrt{3/8}\pi/m_c$ for $q^2 \ll m_c^2$, which is similar to the estimate of $d \approx .25\,\mathrm{fm}$ [12] for the process of forward J/ψ coherent photoproduction with a charmonium realistic wave function. For large q^2 in the Coulomb atom approximation we find $d^2(q^2)/d^2(0) \approx 4m_c^2/q^2$ for the dominant amplitude when gluons are attached to the same c-quark. Hence we will use in our analysis the interpolation formula

$$d^2(q^2)/d^2(0) \approx (1 + q^2/4m_c^2)^{-1}, \tag{4}$$

with $d_0 = .25\mathrm{fm}, m_c = 1.5\,\mathrm{GeV}$.

We choose the kinematics where $\tilde{x} \geq x_{sh} \equiv 0.01$, hence, the shadowing and antishadowing effects in the nucleus parton density in the process of hard interaction are small, $g_A(\tilde{x}, q^2) \approx A g_p(\tilde{x}, q^2)$, and Eq.(2) leads to a cross section which is approximately linear in A.

Now we demonstrate that diagrams where the ladder is attached to gluons belonging to different nucleons of the nucleus give a small contribution for realistic nuclei in spite of been enhanced by a combinatorial factor $\propto A^{1/3}$. For simplicity we consider scattering at central impact parameters for the rapidity interval given by Eq.(3). In this case one of the partons should carry β_1 light cone fraction of the nucleon momentum, which is comparable to $\tilde{x}$, while the second one is allowed to have any $\beta_2 \geq \beta_1$. To obtain an upper limit for the ratio, R_2, of contributions of these diagrams to that described by diagram in Fig.1 we assume that momentum transfers in the interactions with two partons of the nucleus are $q_1^2 \sim q_2^2 \sim q^2/4$. Emission of two partons with $p_t = \sqrt{q^2}/2$ to the same angular interval as for the single parton with $p_t = \sqrt{q^2}$ requires $\beta_1 = \tilde{x}/2$ and $\beta_2 \geq \beta_1$. Hence in this approximation R_2 is expressed through the number of gluons in the cylinder of radius $d/2$ with $\beta_1 = \tilde{x}/2, \beta_2 \geq \beta_1$ as (cf. Eq.(1)) :

$$R_2 = \frac{\pi[d(q^2)]^2}{4} \frac{g(\frac{\tilde{x}}{2}, \frac{q^2}{4}) T(b=0)}{g(\tilde{x}, q^2)} \cdot 2 \int_{\frac{\tilde{x}}{2}}^{1} d\beta_2 g(\beta_2, \frac{q^2}{4}), \tag{5}$$

where $T(b) = \int_{-\infty}^{\infty} \rho_A(b, z) dz$ is the standard thickness function normalized to A. A factor of two in the nominator is due to the presence of two different attachments of gluons to partons of the target. For the J/ψ production, using Eq.(4) we find, for example, for $q^2 = 4\mathrm{GeV}^2, \tilde{\mathrm{x}} = \mathrm{x_{sh}}$, $R_2 < 5\%$. The factor R_2 stays small at larger $\tilde{x}$ due to decrease of parton densities with x. The same conclusion is valid for $\tilde{x} \geq 0.1$ where contribution of scattering off quarks becomes noticeable. Note also that the momentum balance in the case of interaction with two different partons is strongly different than in the case of interaction with a single parton leading to possibility to suppress this contribution using kinematic cuts.

Hence we conclude that, in the discussed kinematics, significant deviations from the linear A-dependence can arise only due to possible *inelastic* interactions of the dipole with other nucleons of the nucleus. The change of the probability of the gap survival with A:

$$P_A^{gap} \equiv \frac{A_{eff}}{A} = \frac{d\sigma_{\gamma A\to J/\psi X}}{dq^2 d\tilde{x}} / A \frac{d\sigma_{\gamma N\to J/\psi X}}{dq^2 d\tilde{x}}, \tag{6}$$

which is formally a higher twist effect in d^2 has a physical meaning of the probability for a small dipole to pass through the media without inelastic interactions for the energy $W_{\gamma N}$.

This effect can be expressed through the profile function for the dipole - nucleus scattering, $\Gamma_{dip,A}(x,d,\vec{b})$, which is the Fourier conjugate of the elastic dipole - A amplitude. It is normalized so that $\sigma_{tot}(dip-A)(x,d) = 2\int d^2b\Gamma_{dip,A}(x,d,\vec{b})$. The range of gluon x probed in this case is of the order $x \equiv m^2_{J/\psi}/W^2_{\gamma N}$ (and somewhat smaller if one uses the charmonium model for the J/ψ wave function like in [12]). In the dynamics driven by inelastic interactions $\left|\Gamma(x,d,\vec{b})\right| \leq 1$. Application of S-channel unitarity (essentially the probability conservation, cf. [13]) allows one to demonstrate that the probability for the dipole not to interact inelastically is equal to $\left|1-\Gamma(x,d,\vec{b})\right|^2$ leading to

$$A_{eff} = \int d^2b\, T(\vec{b}) \left|1-\Gamma(x,d,\vec{b})\right|^2 . \tag{7}$$

Here we neglect fluctuations in the size of the dipole which is a good approximation for the regime of moderate absorption where *average* interaction strength enters into the answer. In the case of large absorption the filtering effect takes place leading to enhancement of the contribution of small dipoles. A more detailed treatment will be given elsewhere.

Choice of kinematics with $\tilde{x} > x_{sh}$ results in dominance of hard interaction at small impact parameters. Thus, using a heavy nucleus as a target one can probe propagation of a small dipole through ~ 10 fm of nuclear matter and determine $\left|1-\Gamma(x,d,\vec{b})\right|$.

To estimate the suppression effect as given by Eq.7 we use two popular complementary models for the interaction of a small size dipole with the matter. One is the eikonal model where the small size dipole interacts via multiple rescatterings off nucleons with the strength given by the dipole - nucleon total cross section. Deviations of the dipole - nucleus interaction from $\propto A$ is a higher twist effect since the interactions with $n \geq 2$ - nucleons is $\propto d^{2n}$. Second model is the leading twist shadowing model which includes only two gluon attachments to the dipole. In this case deviations from the linear regime in A are due to soft interactions of the two gluons with the nucleus.

In the eikonal model, neglecting fluctuations of the $c\bar{c}$ transverse size we obtain:

$$\Gamma(x,d,\vec{b}) = 1 - \exp(-\sigma_{dip-N}(x,d)T(\vec{b})/2), \tag{8}$$

where $\sigma_{dip-N}(x,d)$ is given by Eq.(1). Since for heavy nuclei $T(0) \approx 2\,\mathrm{fm}^{-2}$, $P^{gap}_A \approx \exp(-\sigma_{dip-N}(x,d)T(0))$ becomes small already for $\sigma \sim 5\,\mathrm{mb}$ which corresponds to $x \sim 10^{-3}$. Hence in this model a large suppression effect is expected which grows with $W_{\gamma N}$ and, for fixed $W_{\gamma N}$, decreases with increase of q^2, see Fig.2 (the curves for $q^2 = 50\,\mathrm{GeV}^2$ aim to illustrate the trend of the t-dependence of P^{gap}_A, the actual measurement for this range of t will require a long running time).

An alternative model is the leading twist approximation over parameter $\Lambda^2_{QCD}/(4m_c^2+q^2)$ for the dipole scattering off the nucleus which was used for the description of coherent J/ψ production. Contrary to the eikonal approximation this approach accounts for essential nuclear modification of the nuclear parton distributions at small x. Since in the leading twist Eq.(1) describes inelastic dipole - nucleus cross section, the probability for a dipole of the size d to pass through the nucleus without inelastic interactions is

$$P^{gap}_A = \frac{1}{A}\int d^2b\, T(\vec{b})[1-\sigma_{dip-N}(x,d)\frac{g_A(x,Q^2,\vec{b})}{g_N(x,Q^2)}], \tag{9}$$

where $Q^2 = \lambda/d^2$ and $g_A(x,Q^2,\vec{b})$ is the gluon density of the nucleus in impact parameter space ($\int g_A(x,Q^2,\vec{b})d^2b = g_A(x,Q^2)$). In the kinematic range $x \geq 3\cdot 10^{-3}$ where shadowing effects are still small one can unambiguously calculate the shadowing correction as a function of $\vec{b}$ through the diffractive gluon parton distribution function (pdf), $g_{diff}(x,x_{I\!P},Q^2)$ which is measured in hard processes at HERA. Higher order rescatterings could be estimated by introducing $\sigma_{eff}(x,Q^2) = \int_x^{0.01} dx_{I\!P}\, g_{diff}(x,x_{I\!P},Q^2)/g_N(x,Q^2)$, for details see [14].

The very small x and low virtuality diffractive pdf's one has to use for such an analysis are not reliable as they involve extrapolations from larger Q^2 and x. A straightforward application of the data leads to a very strong shadowing of g_A and hence to a small absorption, see Fig.2 (dotted line). However it is very difficult to envision leading twist (LT) dynamics where partons of nucleons at a given impact parameter, b, would screen the nuclear pdf below the maximal value of generalized gluon density $g_N(x,Q^2,\vec{\rho})$ of one nucleon at this b (in the Glauber model for the nucleon-deuteron interaction this condition corresponds to $\sigma(hD) \geq \sigma(hN)$). For the limit of large A this implies a condition

$$g_A(x,Q^2,\vec{b}=0) \geq g_N(x,Q^2,\vec{\rho}=0). \tag{10}$$

An effective way to implement this condition is to use the eikonal expression for screening of $g_A(x,Q^2,\vec{b})$:

$$\frac{g_A(x,Q^2,\vec{b})}{g_N(x,Q^2)} = \frac{2}{\sigma_{eff}(x,Q^2)}[1-\exp(\frac{-T(\vec{b})\sigma_{eff}(x,Q^2)}{2})],$$

which leads to $g_A(x,Q^2,\vec{b})/g_N(x,Q^2) \leq 2/\sigma_{eff}(x,Q^2)$ and find maximal value of $\sigma_{eff}(x,Q^2)$ which satisfies Eq.10 for large $T(b)$. The t-dependence of the gluon generalized parton distribution $g_N(x,t)$ is measured at HERA in the exclusive vector meson production. For $x \sim 10^{-4}$ exponential fits ($\exp(Bt)$) find $B \sim 5\mathrm{GeV}^{-2}$. Using this fit we find $\sigma^{max}_{eff} = 4\pi B \sim 27\,\mathrm{mb}$. This geometrically constrained LT (gcLT) model leads to the solid curve in Fig.2. One can see that the magnitude of the suppression predicted by such gcLT model is rather close to that obtained in the eikonal model, the effect of

absorption is large and strongly depends on energy and q^2.

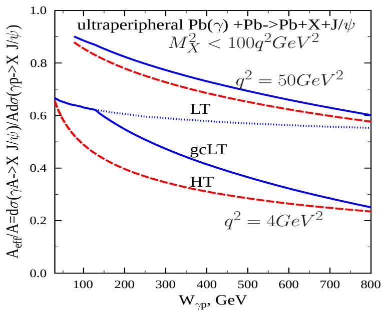

FIG. 2: The rapidity gap survival probability as a function of $W_{\gamma N}$ for $q^2 = 4\,GeV^2$ and $q^2 = 50\,GeV^2$

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To determine for what kinematic range at LHC the measurements of cross section of the ultraperipheral process $A + A \to A + J/\psi + gap + X$ are feasible we used the standard expression for the photon flux generated by the relativistic ions. To calculate the cross section of $\gamma p \to J/\psi + \, gap \, + X$ we adopted the QCD motivated parametrization of [10] which fits all relevant HERA data using CTEQ6L parton distributions [15]. P_A^{gap} was calculated within the models described above. We imposed the cut: $\tilde{x}_{min} \geq 0.01$ corresponding to $M_X \leq 10\sqrt{q^2}$.

Since it is possible to determine experimentally which colliding ion serves as the source of photons we don't account here for the symmetrical contribution from another ion which increases the counting rate by a factor of two. The results presented in Fig.3 indicate that for the planned integrated luminosity for one month of running per year $4.2 \times 10^5\,\text{mb}^{-1}$, it will be possible to measure P_A^{gap} in a wide range of q^2 up to $W_{\gamma N} \sim 1$ TeV. A much larger range of q^2 will be feasible for the process $\gamma + A \to \rho + \text{gap} + X$ both due to a larger elementary cross section and absence of the suppression due to a small branching ratio for $J/\psi \to l^+l^-$. Measurements with ρ's will also allow to determine up to what q^2 the end point contribution which corresponds to very small $P_A^{gap} \propto A^{-2/3}$ gives a noticeable contribution and at what q^2 the leading twist contribution leads to $P_A^{gap}(\rho) \approx P_A^{gap}(J/\psi)$.

In conclusion, we find that a study of the J/ψ in UPC with rapidity gaps will allow to determine the pattern of absorption for the interaction of small dipoles with $0.15fm \leq d \leq 0.25\,\text{fm}$ up to $W_{\gamma N} \sim 1$TeV which corresponds to interaction with gluon fields with x down to 10^{-6} for virtualities of $\sim 4 \div 10\,\text{GeV}^2$. The ability to vary both q^2 and $W_{\gamma N}$ will allow to separate the regions where opacity should be large and where the high energy color transparency will hold. Extension of these measurements to smaller q^2 will help to get better understanding

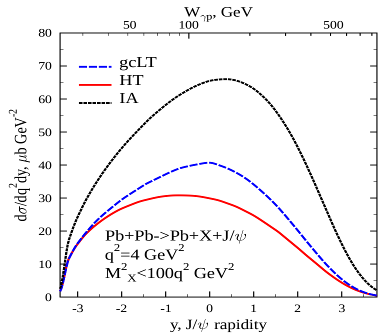

FIG. 3: The rapidity distribution for the J/ψ photoproduction in the UPC $Pb + Pb \to Pb + J/\psi + gap + X$.

of soft diffractive dissociation induced by a small dipole. The discussed J/ψ measurements will also serve as an important benchmark for the studies of J/ψ production in the heavy ion collisions at the LHC as well help to understand the possible role of small dipoles in generating strongly fluctuating pedestal in the inelastic pp collisions.

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